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What colour is a shadow?

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Abstract
What colour is a shadow? Black, grey, or some other colour? This paper describes how to use a digital camera to test the hypothesis that a shadow under a clear blue sky has a blue tint. A white sheet of A4 paper was photographed in full sunlight and in shadow under a clear blue sky. The images were analysed using a shareware program called *ImageJ*. The average red, green and blue pixel values in a region of interest drawn on a photo of the paper in sunlight and shadow were 0.3, 0.32, 0.38 and 0.2, 0.3, 0.5 respectively, demonstrating that a shadow under a blue sky has a blue tint. The experiment would be a useful exercise for a science class.

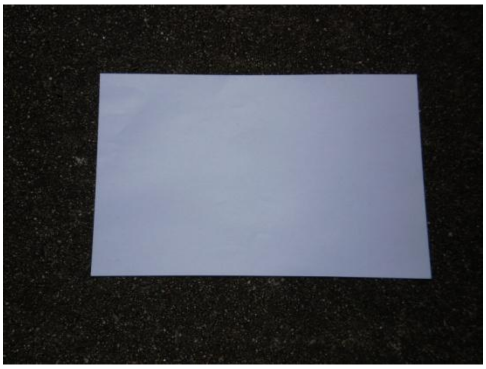
Introduction
What colour is a shadow? The answer to this question may seem obvious – black! However, on further reflection we might come to the conclusion that shadows are grey. This question was prompted whilst sitting outside my house fairly early one sunny morning marking exam papers when I noticed[1] (for the first time ever) that the shadow of my pen on the white exam paper had a slight blue tint – almost subliminal in nature. Was this real or just a pigment of my imagination? Could the blue tint be produced by the clear blue sky reflecting off the white paper? An experiment was required to answer this question – so I stopped marking[2] and got out my digital camera and a white sheet of A4 paper and asked one of my children to act as a shadow.

Method
A digital camera was used to photograph of a white sheet of A4 paper placed in the sun and then in shadow. The photo of the sheet of paper in sunlight serves as a control. Some cameras have a white balance feature so that when a photo of a white object is taken the red, green and blue (RGB) values are adjusted to display white. The camera used in this experiment did not have this feature, but this did not matter as the shadow RGB values are compared to the white sheet RGB values. An advantage of taking two separate photos is that the difference in brightness between full sunlight and shadow can be measured.

The experiment was performed with an Olympus FE-220 7 megapixel digital camera. Figure 1 shows the paper in sunlight and shadow. When the coloured images are viewed (also available in the online version of the journal at stacks.iop.org/physed/44/292) the shadow image has an obvious blue tint. Although the camera used in this experiment does not have manual controls, exposure

[1] Many readers of this journal will appreciate how easy it is to become distracted whilst marking exam papers – maybe it is ADD – assessment distraction disorder.
[2] I did get my exam results in on time.

information is available when viewing the image in a viewing program. On a Mac, exposure information can be obtained from the *Preview* program by selecting *Tools/Get Info*. On a Microsoft Windows system the *Picture and Fax viewer* program can be used to obtain exposure information. Other programs can be used as well, for example, *Adobe Bridge* CS3 and a shareware program called *IrfanView* (http://www.irfanview.com/).



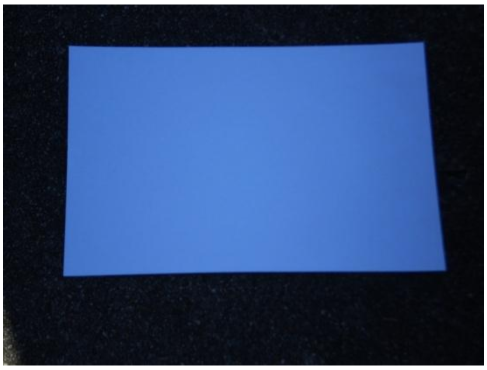


Figure 1 (a) Left - photo of an A4 sheet of paper in direct sunlight, (b) in shadow.

The two images were loaded onto a MacBook Pro and a free program called *ImageJ* (http://rsbweb.nih.gov/ij/) used to analyse the image data. The following text describes what was done in the form of an instruction manual so the experiment can be readily repeated.

1. Run *ImageJ* and load in the image you want to process.

2. Select *Image/Type/RGB Split.* One colour channel of the RGB image will be displayed with "1/3 (Red)" written on the left-hand side of the bar at the top of the image window. This indicates that the first of the three RGB images is being displayed, which is red. You can change which colour channel is displayed using the '<' and '>' keys. Images can also be split into red, green and blue components by selecting *Image/Color/RGB Split*[3]. Three grey scale images will be displayed with each image showing the relative amounts of red, green and blue in the image. An individual image may be selected by clicking on the bar at the top of the image frame.

3. Select one of the shape icons (e.g. square) and draw a region-of-interest (ROI) on the image.

4. Save the ROI so that it can be re-used. To do this, go to *Analyse/Tools/ROI Manager/*. Click on Add(t) and a code will appear in the ROI manager window. You can change this code to something more understandable by clicking on the *Rename* button. For example, you could rename the code as "dark sky roi" or "bright sky roi" as appropriate. Click on the *Save* button to save the ROI. Choose an appropriate folder to place the ROI files – the same folder that the sky images reside in would be a good place. To re-load an ROI, click on the Open button and select the ROI file. The

[3] ImageJ uses American spelling, being a computer program produced in the USA; however, in this article Australian/British spelling is used.

name will appear in the ROI manager window – click on the name and it will appear on the image.

5. Go to *Analyse/Set Measurements* and ensure that the mean grey level and standard deviation boxes are ticked. Set the *Min and Max Grey Level* option so that the maximum and minimum pixel levels are displayed. If the maximum grey level is 255 this will probably invalidate the results as the maximum pixel value is likely to be greater than 255 by an unknown amount.

6. Select one of the colour channels, e.g. red and choose *Analyse/Measure*. A box will appear showing the mean and standard deviation of the pixel values within the ROI.

7. Repeat the process for the other two colour channels.

Results

The basic results are shown in table 1 and figure 2 shows the results in graphical form. Table 2 shows the data used to calculate the difference in brightness between the paper in sunlight and in shadow. In this case the paper in sunlight is 14.5 times brighter than in shade, or put another way round the shadow is only 6.8% as bright as the paper in sunlight (table 3). A statistical test known as the *standard error of the difference* (SED) test is a technique that can be used to compare whether or not two samples come from the same population [1]. Normally if the SED is more than three times greater than the difference between the means, the difference is significant. In this case the SED is several thousand times greater than the difference between means and so the result obtained is highly significant.

The SED is defined as: $\sqrt{\frac{\sigma_1^2}{n_1}+\frac{\sigma_2^2}{n_2}}$ Where σ is the standard deviation of the pixel values and n the number of pixels.

Table 1. Mean ± one standard deviation for a sunlight and shadow ROI. The RGB values have been normalised so that the sum total is unity.

	Pixel values		Normalised RGB values	
	sunlight	shadow	sunlight	shadow
red	128.6 ± 6.0	81.4 ± 4.1	0.30	0.2
green	137.5 ± 7.0	124.5 ± 5.3	0.32	0.3
blue	160.0 ± 6.2	206.6 ± 5.7	0.38	0.5

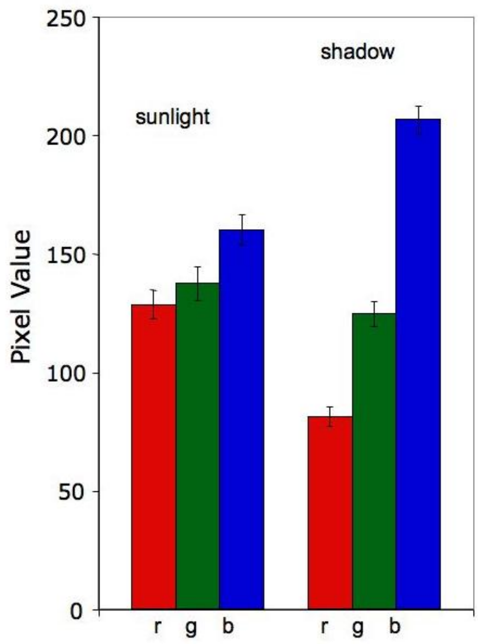


Figure 2. Measured red, green and blue pixel values for a piece of paper in sunlight and in shadow.

Table 2. Mean pixel values, standard error of the difference (SED), difference between means and the difference between means divided by the SED.

Mean pixel values (11760000 pixels)		SED	Difference between means	Difference between means divided by SED
Sunlight	Shadow			
128.5	81.3	0.00671654	47.2	7029
137.5	124.5	0.00813639	13.0	1594
160.0	6.2	0.00778961	46.5	5970

Table 3. Table showing the mean grey scale pixel value within a sunlight and shadow ROI and corresponding camera exposure time and *f* number. In both cases the speed of the CCD was ISO 64. (N.B. The difference in the area of one *f* number (f_1) compared to another (f_2) is $(f_1/f_2)^2$, taking note of the fact that the smaller *f* number is a larger aperture than a larger *f* number).

	Mean pixel value	Exposure time (s)	f number	Product
Sunlight	142	0.0005315	8.5	
Shadow	137.5	0.003848	5.9	
Exposure factor	0.97	7.24	2.08	14.5

Discussion

An important feature to notice is that the error bars (the standard deviation of the pixel values within the ROI) are much smaller than the mean pixel values for the respective RGB channels. In all cases the difference between the means is very much greater than the SED and so the results obtained are extremely unlikely to have been obtained by chance.

Note that the piece of paper exhibits a slight blue excess. This could be because the white balance of the camera is slightly out or because the paper is receiving a significant amount of blue from the surrounding sky which is being mixed with the direct sunlight. Whether this is so could be the subject of another experiment. For example, a piece of white paper could be placed close to the exit of a piece of pipe so that most of the surrounding sky is blocked off.

This experiment also enables the difference in brightness between a piece of white paper in sunlight and shadow to be estimated. In this case the shadow was about 14.5 times dimmer than the sheet of paper in direct sunlight.

The experiment described in this paper would be fairly easy and cheap to implement as a classroom experiment. If a digital camera, sheet of white paper and a computer with Internet connection are available then the experiment is essentially free.

Acknowledgement

Thanks to James Hughes for the loan of his shadow.

References

[1] Reichmann W J 1964 *Use and abuse of statistics*, (London: Penguin).